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A COMPARISON OF VERTICAL AND HORIZONTAL GPR VELOCITY ESTIMATES IN ALLUVIAL SEDIMENTS

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Abstract

We have measured the horizontal and vertical electromagnetic velocity through an alluvial, sand-and-cobble aquifer near Boise, Idaho. To measure the horizontal velocity, we deployed antennas in two wells 6.9 m apart. To measure the vertical velocity, we placed one antenna on the surface adjacent to a well and lowered the other antenna down that well. We collected data at three wells; two wells at either end and a well located in between the two end wells. We thus have one measure of the horizontal velocity and three measures of the vertical velocity. The horizontal and vertical velocity are essentially the same below the water table at 2 m depth. In the vadose zone, the velocities differ, but we think that refracted waves cause the velocity differences. The directional independence of the velocities indicates that we can assume isotropic models in our interpretation of the aquifer.

Introduction

The presence of velocity anisotropy constrains our choice of models that accurately describe the earth. If velocity anisotropy exists, our models must account for the directional dependence of the physical properties in the ground. In addition, velocity anisotropy in the shallow subsurface is most likely caused by fine scale layering. This fine scale layering is difficult to image geophysically because of the wavelengths of the propagating energy are much greater than the layer thickness. The presence of velocity anisotropy may indicate that fine scale layering exists. This layering also must be incorporated in our models of the earth. We can test for the presence of velocity anisotropy by comparing the horizontal and vertical velocity estimates of the subsurface.

We have sampled the subsurface at an unconfined aquifer near Boise, Idaho with horizontally and vertically propagating electromagnetic (EM) radar waves to determine if velocity anisotropy exists at the site. The Boise Hydrogeophysical Research Site (BHRS) was designed to study the subsurface using a variety of methods, including geophysical techniques. Located near the Boise River, the subsurface of the BHRS consists of alluvial, sand-and-cobble sediments. Eighteen wells were cored through the sediments to determine the grain size and composition of the sediments (figure 1). In addition, we can deploy downhole geophysical instruments, such as ground penetrating radar, in the wells to determine the physical properties of the subsurface. Thus, we can compare horizontal velocity estimates directly with vertical velocity estimates for nearly the same location in the subsurface.

Methods

Level Run

To determine the horizontal EM velocity, we acquired travel time data with Ground Penetrating Radar (GPR) using 250 MHz borehole antennas placed in different wells (figure 1). The transmitting antenna was lowered in well B6 and the receiving antenna was lowered in well B3. The travel time was measured with the transmitter and receiver at the same depth in each well. The antennas were lowered 0.1

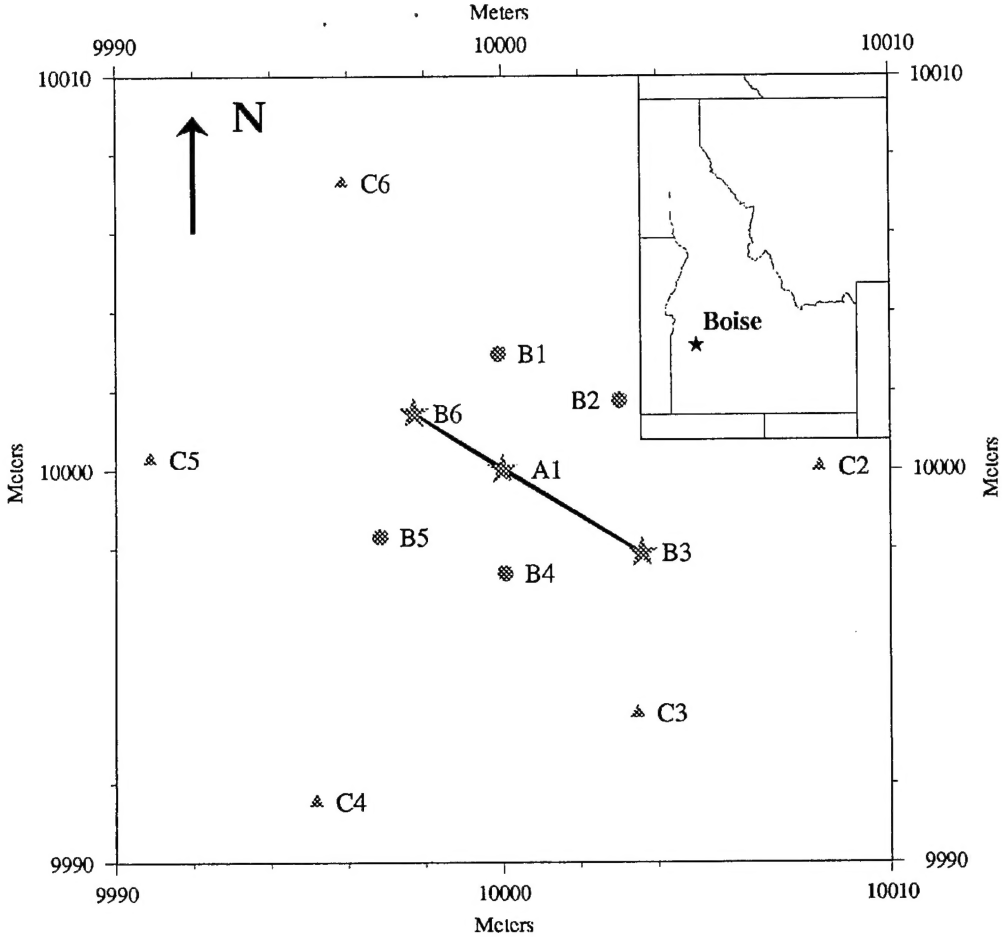

Figure 1. A map of the BHRS showing the locations of the wells used to characterize the aquifer. In this study, we use data from wells B6, A1, and B3. The solid line indicates the level run profile. The transmitter was lowered down well B6 and the receiver was lowered down well B3. The stars denote the locations of the VRPs in wells B6, A1, and B3. The distance between wells B6 and B3 is 6.9 m.

m and another travel time was recorded. This procedure was repeated to the bottom of the shallower well. We refer to data collected with this acquisition geometry as a level run, because the source and receiver are "level" in the wells (These surveys are also referred to as zero offset profiles). To estimate the horizontal velocity, we divided the distance between the wells, 6.9 m, by the travel time from the transmitter to the receiver. Figure 2 displays the travel time data and the velocity determined from the first arriving energy.

VRPs

Vertical radar profiles (VRPs) measure the vertically propagating EM energy. The borehole transmitter antenna was positioned at the surface near the well and the receiver antenna was lowered down the well. The center point of the transmitter was 0.83 m from the well. At receiver depths below 4 m, the energy propagates at a 78° angle from the horizontal. Also, the energy refracts downward at the water table because of the lower velocities in the saturated sediments. The energy was recorded every 0.1 m depth. Figure 3 shows the data acquired at well B6; the other two VRPs are similar.

To determine the vertical EM velocity, we used a linear, weighted, least-squares inversion method. The inversion method computes the interval velocities with depth from the first arrivals. To linearize the

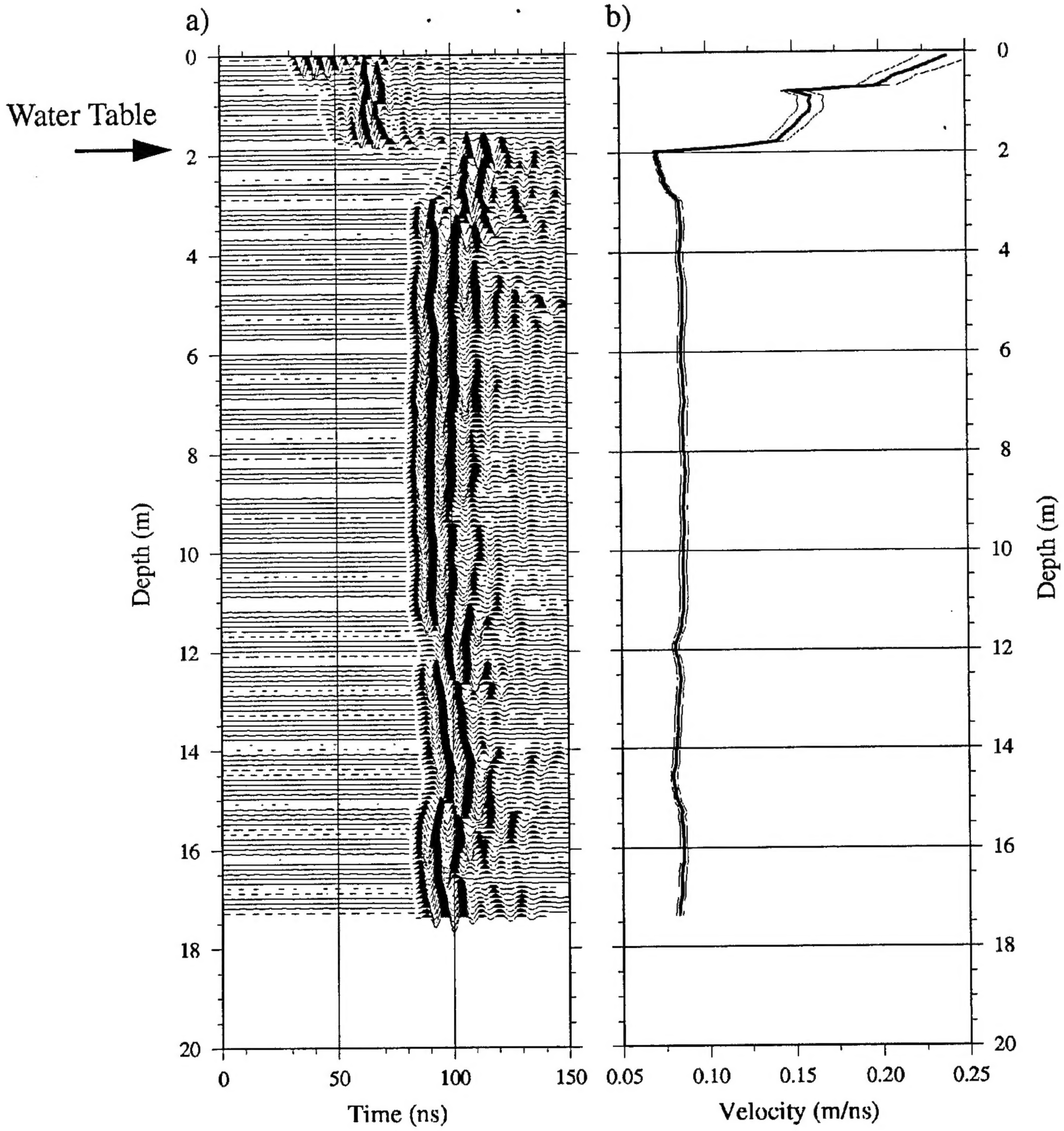

Figure 2. Level run between wells B6 and B3. The radar data is on the left (a) and the velocity profile from the first arrivals is on the right (b). The thin lines on either side of the thick velocity profile are the velocities obtained by adding or subtracting 2 ns to the arrival. In (a), the white line indicates the first arrival times used in the velocity calcu-

problem, we assume that the energy propagates in straight lines from the transmitter to the receiver and that each layer has a constant slowness (reciprocal velocity) and thickness (0.25 m in the inversion). The routine then calculates the slowness for each layer, which we convert to velocity. To provide a more realistic velocity model, we regularize the solution to smooth the velocity fluctuations. Importantly, inverse methods provide estimates of the error bounds for the inverted velocity estimates.

The data for the inversion are the first arrivals from above 10 m depth or so. Below 10 m, the arrivals are difficult to confidently pick because of the lower amplitude energy compared to the noise in the data. We also assume that the standard deviation of our arrival time picks is 0.1 ns. The 0.1 ns standard deviation is derived from statistics using picks by five different people of a radar data set. The data determine a layered velocity model to about 10 m depth with estimates of the velocity error.

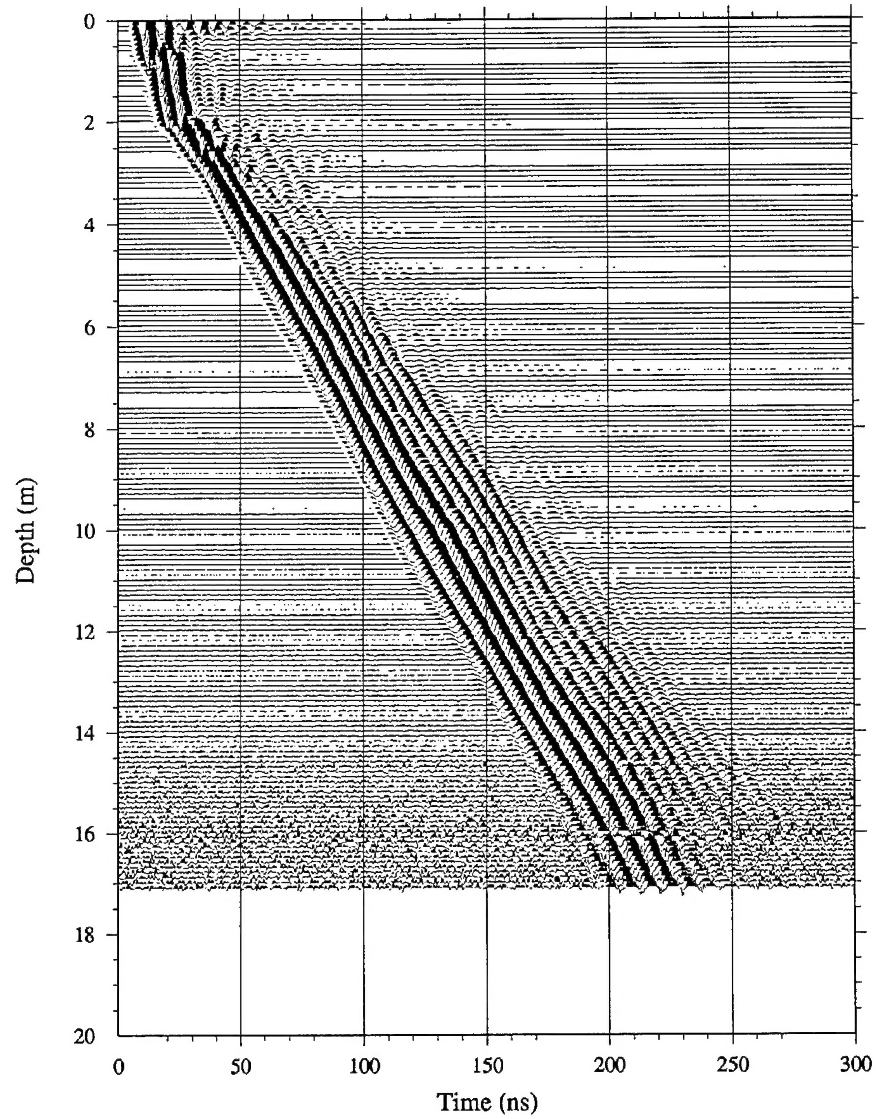

Figure 3. The VRP collected at well B6. The solid white line indicates the arrival times used in the layered velocity inversion. Only arrivals above 10 m or so are used in the inversions of the three VRPs.

Results

Horizontal Velocity

From the level run, the horizontal EM velocity ranges from 0.24 m/ns near the surface to 0.07 m/ns at 2 m depth. Below 3 m, the horizontal velocity fluctuates around 0.085 m/ns. The sharp delay in travel time at about 2 m depth corresponds to the water table. Near the surface, the EM energy is probably propagating in air. Air has an EM velocity of 0.3 m/ns. According to Fermat's Principal, the energy will follow the path of least time. The computed horizontal velocity is less than 0.3 m/ns because the distance used to calculate the horizontal velocity was the well separation, 6.9 m. The actual travel path was probably greater than the distance between the wells; from the transmitter to the surface, along the surface, then down the well to the receiver. The true travel path (D_t) is longer than the well separation (D_s), so the calculated horizontal velocity (V_c) is slower:

$$D_t > D_s \tag{1}$$

$$\frac{D_t}{t} > \frac{D_s}{t} = V_c \tag{2}$$

where t is the observed travel time.

The sharp velocity decrease at about 0.75 m may indicate that the energy is propagating through undisturbed sediments below 0.75 m. As part of the well construction, a concrete base was placed around the well to a depth of about 0.5 m to 1 m. The velocities above this depth are probably the result of refractions through the air and through this concrete base. These velocities are probably not representative of the aquifer sediments.

At 2 m, the horizontal velocity decreases sharply to 0.07 m/ns, then increases to about 0.085 m/ns at about 3 m. Below 2 m, the pores are water-filled. Water has a much slower velocity, 0.034 m/ns, than air, so water-filled pores will dramatically lower the velocity. The EM velocity of sands and cobbles similar to those present at the BHRS are about 0.18 to 0.11 m/ns, corresponding to dielectric constants of 3 to 6 (Hubbard et al., 1997). The small fluctuations in the horizontal velocity below the water table probably indicate small changes in the porosity of the material because the aquifer is relatively homogeneous mineralogically.

Vertical Velocity

Figure 4 shows the VRP inversion for vertical EM velocity estimates for the three wells and the

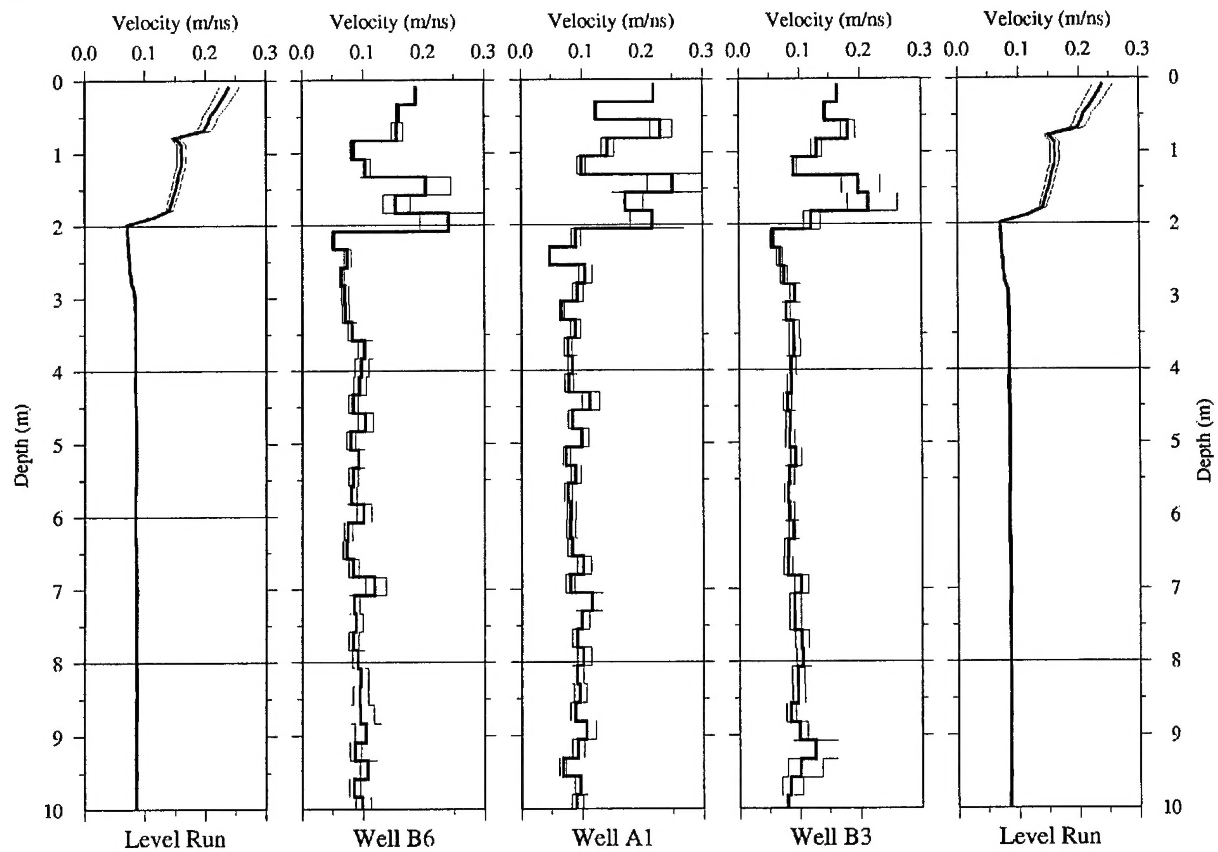

Figure 4. Velocities from the level run and the 3 VRPs. The level run plots on the left and right are identical and are included twice to help clarify the velocity changes between the wells. The inverted velocity for the VRPs are the thick solid lines. The thin solid lines are the 95% confidence bounds determined from the standard deviation of the velocity

level run velocities. The vertical velocities range from 0.25 m/ns in the upper 2 m to about 0.045 m/ns at

about 2.5 m depth. As in the level run data, the water table causes the dramatic velocity change at 2 m. Between 1 to 2 m depth, the vertical velocity varies from about 0.1 m/ns to about 0.2 m/ns. This velocity change may indicate a change in porosity in the vadose zone. The higher vertical velocity probably corresponds to a high porosity layer. Below 2 m, the vertical velocity gradually increases from 0.045 m/ns to about 0.085 m/ns at 3 m. Interestingly, the overlying high velocity zone, combined with the slow velocity just below the water table, may indicate that the high porosity zone exists between 1.25 m and 2.5 m. As mentioned previously, the presence of air or water in the pore space controls the EM velocity. Sediments with air-filled pores will have a fast velocity whereas sediments with water-filled pores will have a slow EM velocity. Thus, the large vertical velocity change from fast to slow across the water table indicates a change from air-filled pores to water-filled pores and not a change in sediment composition. Below 3 m, the velocity fluctuates about 0.085 m/ns.

Discussion

Figure 5 compares the horizontal EM velocity to the average vertical EM velocity. Below 2 m, the horizontal and vertical velocities are very similar. Except between 8 and 9 m, the range of the minimum and maximum vertical velocity overlaps the horizontal velocity. However, the horizontal velocities are within the 95% confidence bounds of the vertical velocity estimates.

Below 3 m, the horizontal and vertical EM velocities show small fluctuations about a velocity of 0.085 m/ns. Velocities derived from porosity estimates based on neutron logs show small, smooth velocity changes, even though the porosity changes by 15%. The nearly constant velocity in the aquifer highlights the need for an integrated approach to estimate subsurface physical properties.

Above the water table, the horizontal and vertical velocities differ. Above 0.75 m, the velocity difference is probably due to refractions at the land-air interface and in the disturbed sediments and cement foundation. Between 0.75 m and 2 m, the velocity differences also are probably due to refractions in the adjacent layers. If a thin low velocity layer exists between higher velocity layers, such as between 0.75 m and 1.25 m, the EM energy will tend to propagate in the higher velocity layers as predicted by Fermat's Principal. The velocity assigned to the low velocity layer's depth will be faster than the true layer velocity and will cause the horizontal velocity to appear faster than the vertical velocity.

The horizontal velocity is slower relative to the vertical velocity between 1.25 m and 2 m depth. The horizontal velocity of about 0.15 m/ns is a reasonable velocity for these vadose zone sediments. The vertical velocity is too fast. In the vertical velocity inversion, we assumed straight rays. Because the rays in the upper 2 m or so are not propagating vertically, the energy may refract, resulting in unreasonably fast vertical EM velocity estimates.

In general, the vertical velocity estimates have larger velocity fluctuations than the horizontal velocity estimates. The layered inversion method for the vertical velocities accounts for some of the difference. The vertical velocities are constrained to vary at 0.25 m increments, whereas the horizontal velocities are constrained to 0.1 m steps by the acquisition interval. In the plots, the horizontal velocities are displayed as points with the velocity changing linearly between points. The vertical velocity is displayed with abrupt velocity changes at layer interfaces, creating the blocky velocity distribution. Still, the magnitude of the velocity variations are larger for the vertical velocity compared to the horizontal velocity. Wavefront healing may partially account for the smoother horizontal velocity profile compared to the vertical velocity profile. However, the algorithm used to determine the velocity is probably the most important contributor to the different appearance of the two velocity profiles. The horizontal velocity is computed using the travel time from the transmitter to the receiver, whereas the vertical velocity is calculated using the travel times through the 0.25 m layers. Thus, small errors in picking arrivals from the VRPs influence the vertical velocity profile more than small errors in picking horizontal arrivals.

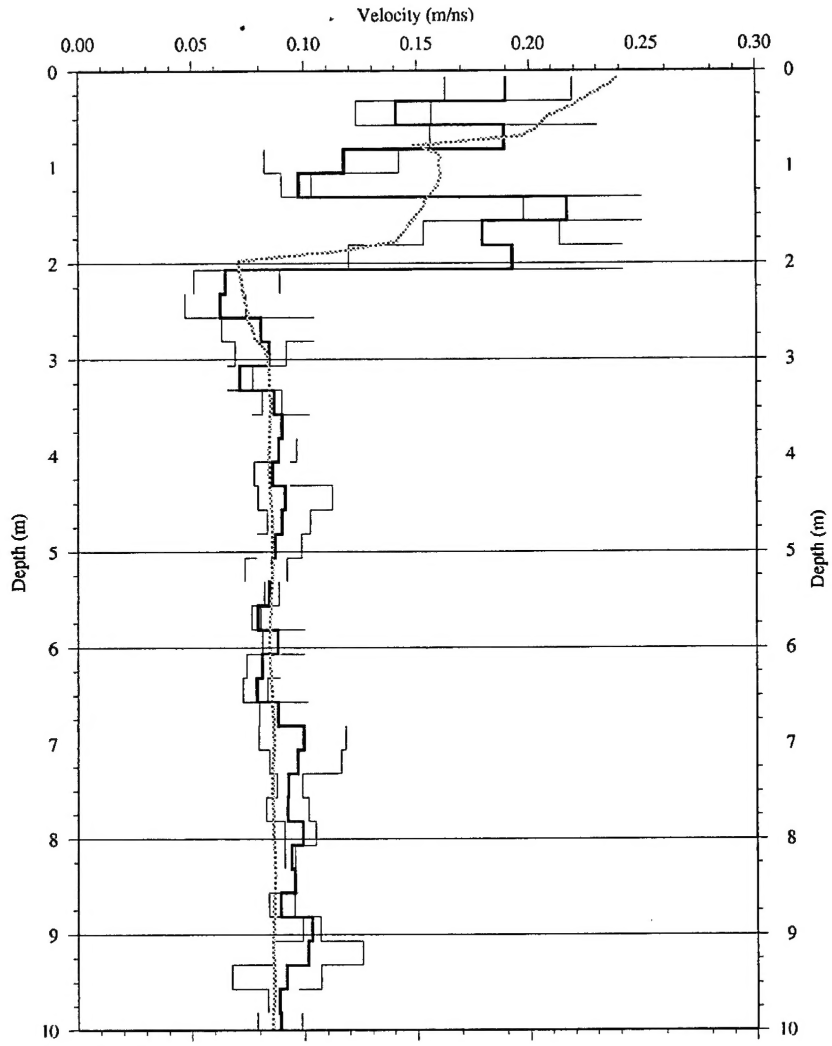

Figure 5. Comparison of the horizontal velocity (gray line) to the average vertical velocity (thick line) at the BHRS. The thin lines are the minimum and maximum values of the velocities from the three VRP velocities at each depth.

At the BHRS, the layering is approximately horizontal. Horizontally propagating energy will refract through faster layers resulting in a faster apparent velocity for the level run depth. The vertically propagating energy will not refract because the layers are approximately horizontal, so vertically propagating energy records the proper velocity for the receiver depth. Thus, the horizontal velocity should be equal to or faster than the vertical velocity due to the layering.

However, below the water table at the BHRS, the average vertical velocity is generally faster than the horizontal velocity. From 3.25 m to 4.75 m and below 6.5 m, the average vertical velocity is faster than the horizontal velocity, although the horizontal and vertical velocities are nearly the same, especially considering the measurement error. The faster vertical velocities may indicate that velocity anisotropy occurs in these layers. Chan and Knight (1999) suggest that fine layering may cause velocity anisotropy. Nearby outcrops of similar alluvial deposits contain lenses in which the grains show preferential orientation. Flowing water during deposition caused the grain alignment. Perhaps fine scale layering within the unit due to preferred orientation of grains causes the apparent velocity anisotropy. Although the anisot-

ropy is very slight, if present at all, this directional velocity dependence may indicate previously unnoticed fine layering.

Conclusions

The horizontal and vertical velocities in the sediments at the BHRS are the same within the error of our measurements. Above the water table at 2 m depth, energy refracted through faster layers may cause the velocity differences. Also, the VRP energy does not propagate vertically in this zone. Below the water table, the velocities are similar. In two zones, the average vertical velocity is faster than the horizontal velocity, although the difference is within the model error. Fine scale layering may characterize these two possibly anisotropic zones. However, at the BHRS, the layering is probably too thick in general to cause velocity anisotropy. The similar horizontal and vertical velocity estimates indicate that we may use isotropic models to characterize the physical properties at the BHRS.

References

1. Chan, C. Y., and R. J. Knight, (1999), Determining water content and saturation from dielectric measurements in layered materials, *Water Resources Research*, 35, 85-93.

2. Hubbard, S. S., J. E. Peterson, Jr., E. L. Majer, P. T. Zawislanski, K. H. Williams, J. Roberts, and F. Wobber, (1997), Estimation of permeable pathways and water content using tomographic radar data, *The Leading Edge*, 16, 1623-1628.